Juno Mission Simulation[1][2]

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Abstract—The Juno spacecraft is planned to launch in August of 2011 and would arrive at Jupiter five years later. The spacecraft would spend more than one year orbiting the planet and investigating the internal structure; determining the amount of global water and ammonia present in the atmosphere, studying convection and deep-wind profiles in the atmosphere; investigating the origin of the Jovian magnetic field, and exploring the polar magnetosphere. Juno mission system management is responsible for mission and navigation design, mission operation planning, and ground-data-system development. In order to ensure successful mission management from initial check-out to final de-orbit, it is critical to share a common vision of the entire mission operation phases with the rest of the project teams. Two major challenges are 1) how to develop a shared vision that can be appreciated by all of the project teams of diverse disciplines and expertise, and 2) how to continuously evolve a shared vision as the project lifecycle progresses from formulation phase to operation phase. The Juno mission simulation team addresses these challenges by developing agile and progressive mission models, operational simulations, and real-time visualization products. This paper presents mission simulation visualization network (MSVN) technology that has enabled a comprehensive mission simulation suite (MSVN-Juno) for the Juno project.

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1. INTRODUCTION

The Juno science is divided into four themes, origin, interior structure, atmosphere, and polar magnetosphere. Each theme area has specific science objectives and measurement requirements. The "origin" theme is to understand global abundances of oxygen and nitrogen via microwave observation of water and ammonia. The "interior structure" theme is to study origins of the magnetic field, core mass, and nature of deep convection via high resolution gravitational and magnetic fields measurements. The "atmosphere" theme is to investigate the penetration depth of belts, zones, the Great Red Spot, and other atmospheric features via sounding of pressure, clouds, winds, and temperature. Finally the "polar magnetosphere" theme is to explore electrodynamic coupling of Jupiter and its satellites via measuring in-situ plasma, fields, waves, and radio emissions.

Using a spinning, solar-powered spacecraft (Figure 1), Juno would map the gravity, magnetic fields, and atmospheric composition of Jupiter from a unique polar orbit. Juno would carry precise high-sensitivity radiometers, magnetometers, and gravity-science systems. 30 of Juno's 33 orbits of 11-day duration would sample Jupiter's full range of latitudes and longitudes. From its polar perspective, Juno combines in-situ and remote sensing observations to explore the polar magnetosphere and determine what drives Jupiter's remarkable auroras. The scientific payload would include a dual-frequency gravity/radio science system, a six-wavelength microwave radiometer for atmospheric sounding and composition, a dual-technique magnetometer, two plasma and energetic particle detectors, a radio/plasma-wave experiment, and an ultraviolet imager/spectrometer. [1], and a near infrared mapping spectrometer.

Section 2 describes the role of mission simulation with respect to the critical mission phases and project lifecycle phases. Section 3 describes the MSVN-Juno framework focusing on four major technology components of real-time operation scenario simulation, multiple view-point visualization, and synchronized simulation control. Section 4 presents the simulation products generated in support of the concept design phase and the preliminary design phase. Finally, Section 5 concludes with the potential impacts of modeling, simulation, and visualization technology in fostering collaborative engineering design by enabling early design validation and verification.

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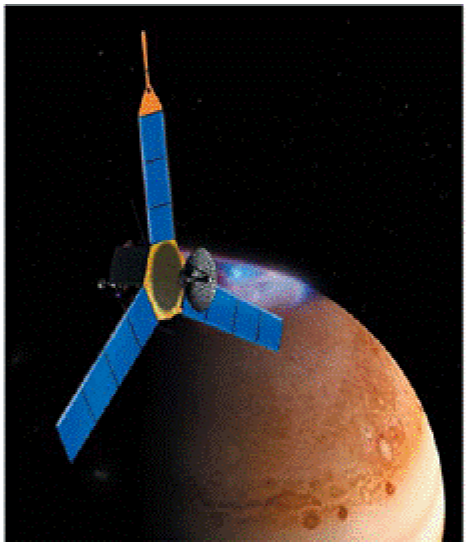

Figure 1. Proposed Juno Spacecraft (New Frontiers Program)

2. Mission Phase Overview

A project is composed of multiple teams representing the spacecraft system, the payload system, the mission system, and science. The spacecraft system team and payload system team are responsible for developing a robust and capable flight system that can perform the science objectives. The mission system team is responsible for navigating the flight system safely and operating the flight and payload system accurately to achieve the science return. The project teams perform these challenging tasks in multiple progressive stages, concept design, preliminary design, detailed design, development, integration and test, and operation. These stages are referred to as project lifecycle phases. At the end of each stage, the project is reviewed for the completion of the current stage with a set of gate products.

The success of a mission is determined by the science return achieved during the final stage, the operation phase. The operation phase of the Juno project would last more than six years, from August 2011 to October 2017. The operation phase is divided into multiple mission phases. For each mission phase, engineering challenges, science opportunities, and operation risks are addressed. The critical mission phases include launch, initial checkout, inner cruise, deep space maneuver, Earth flyby, outer cruise, Jupiter approach, Jupiter orbit insertion (JOI), pre-science orbit (orbits 1 and 2), science orbits (orbit 3–33), and de-orbit. For each mission phase, the science orbits are divided into microwave science orbit group and gravity science orbit group based on the spacecraft attitude control requirements.

The amount of sunlight available to generate power for a spacecraft exploring the outer planets is about 27 times weaker than the sunlight available to a spacecraft exploring the Inner Solar System. Thus, due to the much greater distance of Jupiter from the Sun, the surface area of solar panels required to generate adequate power must be much larger. The Juno spacecraft would use three, ~2-m × 9-m solar panels that would remain in sunlight continuously from launch through end of mission, except for a 20-minute period during the Earth flyby. Before launch, the three solar panels would be folded into four hinged segments so that the spacecraft could fit into the spacecraft faring. The high-gain antenna would be attached to the center of the main hexagonal body of the spacecraft, which shields the engineering systems and science instruments from Jupiter's regions of high radiation [2].

Throughout the Juno mission lifecycle phases the Juno mission simulation team must provide comprehensive mission operation simulation products that can facilitate consistent understanding of the mission objectives and an effective decision-making process among all mission teams. During the formulation phase, mission simulation has been used to analyze various "what-if" scenarios. During the implementation phase, mission simulation system will be used to analyze the impact of subsystem-level performance variation and operation activity plans interacting with the spacecraft system testbed at Lockheed-Martin, mission operation and ground data-system testbeds at the Jet Propulsion Laboratory, and the Juno science operations center at the Southwest Research Institute. During the operation phase, the mission simulation system would be used to verify command sequences and telemetry streams.

The major technical approaches of Juno mission simulation to achieve this goal include:

a. Develop a mission simulation framework that can verify operability with respect to subsystems (power, telecom, propulsion, attitude control, command and data handling (C&DH,) payload subsystem, etc.).

b. Develop seamless interface protocols for tracking flight system performance estimations of the above subsystems throughout the lifecycle.

c. Model the mission operation behavior with sufficient detail and fidelity to aid development, testing, and operations decisions.

d. Interface seamlessly with the products created by Mission Operations, Flight System, and Science Data System.

e. Continuously evolve the simulation framework by infusing new modeling, simulation, and visualization technologies as required.

3. MSVN-JUNO

The Mission Simulation Visualization Network (MSVN) invented by Dr. Richard Weidner at Jet Propulsion Laboratory was used during Saturn orbit insertion (SOI) of the Cassini mission for real-time SOI operation scenario simulation. The simulated SOI events were broadcasted second-by-second, informing various spacecraft activities from six view points. These views were shared simultaneously by many from Los Angeles to New York. At the precise moment when the simulation predicted reception of the signal from the Cassini spacecraft, mission control received a telephone call from the ground station confirming that the spacecraft had entered Saturn orbit safely. MSVN-Cassini made it possible to share the complex mission event as it was happening.

The Juno project adopted the MSVN framework to promote a shared understanding of the complex mission operation activities among the project teams. MSVN facilitates validation and verification of the mission system requirements and designs against the project-level science return requirements by performing a virtual Juno mission. The virtual Juno mission is performed by developing a virtual flight system, a virtual ground system, and a virtual world and applying the mission system design products such as trajectory and operation scenarios on the virtual systems in that virtual world [4]. The three major capabilities of MSVN framework, real-time operation state simulation, multiple view point visualization, and synchronized simulation control are described below.

Real-time Operation State Simulation

Real-time simulation enables visualization of the simulated operation states without involving the cost-prohibitive and time-consuming animation-product generation process. MSVN framework achieves real-time operation-state simulation via creating agile mission models whose computational steps are optimally organized. Each mission model employs a multi-stage data structure that translates the mission information and transforms it into a computationally optimal form. Simulation of dynamic phenomena is very challenging and often requires computationally efficient algorithm development. For example, in order to simulate the magnetic field line that intersects with the Juno spacecraft, the simulation team developed computationally efficient spherical harmonics and a four-dimensional interpolation method.

Multiple Viewpoint Visualization

The MSVN-Juno framework provides multiple channels for visualizing the simulation in order to clarify the multi-dimensional relationship of the complex geometry. There are seven basic channels, and the optional instruments field-of-view (FOV) simulation can be added to the framework. The seven basic channels include three views with respect to Jupiter's inertial frame (nadir, equator, and pole), three views from the spacecraft's inertial frame (solar panel, high-gain antenna, and sub-spacecraft), and one view from an instrument (JunoCam, an optical camera) for education and public outreach. There are several optional channels for instrument FOV simulations. The graphical user interface of MSVN-Juno allows a user to initialize the orbit number and start time of a simulation and to change the channel for simulation viewing. The simulation rate can be specified from subseconds to multiple hours.

Figure 2 is a snapshot of the spectator view during Jupiter orbit insertion (JOI) simulation in which there are highlighted values for the orbit number of zero, the start time of –2 hours before JOI, and the selected channel number of 1. The simulation time shown at the top right corner is relative to the main engine burn time stated at the top left corner. The viewing geometry with respect to the Sun, Earth, and Jupiter are indicated by the yellow, cyan, and blue lines. Figure 3 is a collection of snapshots of four additional views: equatorial view, polar view, Deep Space Network (DSN) view, and an instrument's FOV. The texture of Jupiter can be overlaid with various environmental phenomena information, such as the aurora map shown in the polar view. The DSN view provides three DSN complexes along with the elevation angle lines with respect to the sub-spacecraft position. The instrument view provides the view from the instrument's line of sight.

Synchronized Simulation Control

The multiple channels described above can be synchronously viewed by distributing the simulation over multiple nodes and establishing master and slave relationship among the nodes. The master node controls simulation and distributes the simulation state to the slave nodes via a relay system. One relay system can support as many as 32 slave nodes, and one master can route the simulation states to 32 relay systems. The relay system can maintain sub-second level synchronization among the slave nodes. The distributed simulation capability is used for collaborated design sessions among geographically distributed users. During the design session, the master node can be assigned to any one user, and the slave nodes can be dynamically added or removed. The distributed simulation capability can be also used for viewing multiple operation states simultaneously on a multiple-node system by mapping the channels to the nodes [5].

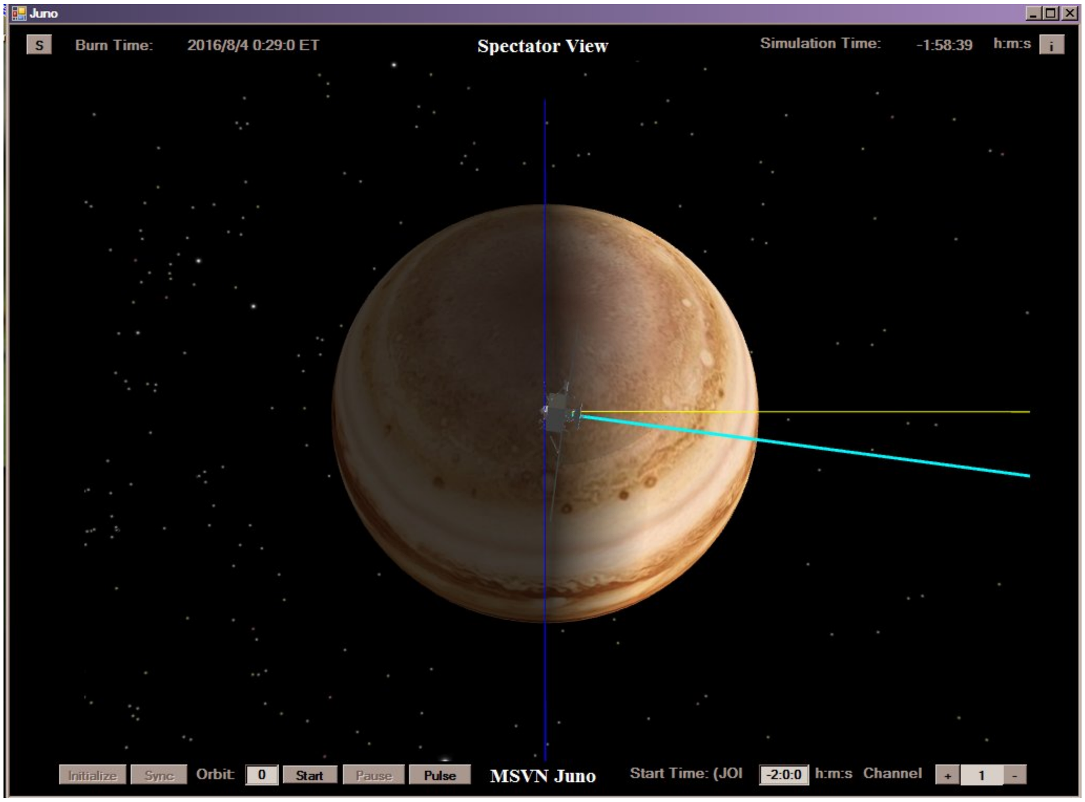

Figure 2. MSVN-Juno Display of Spectator View Channel

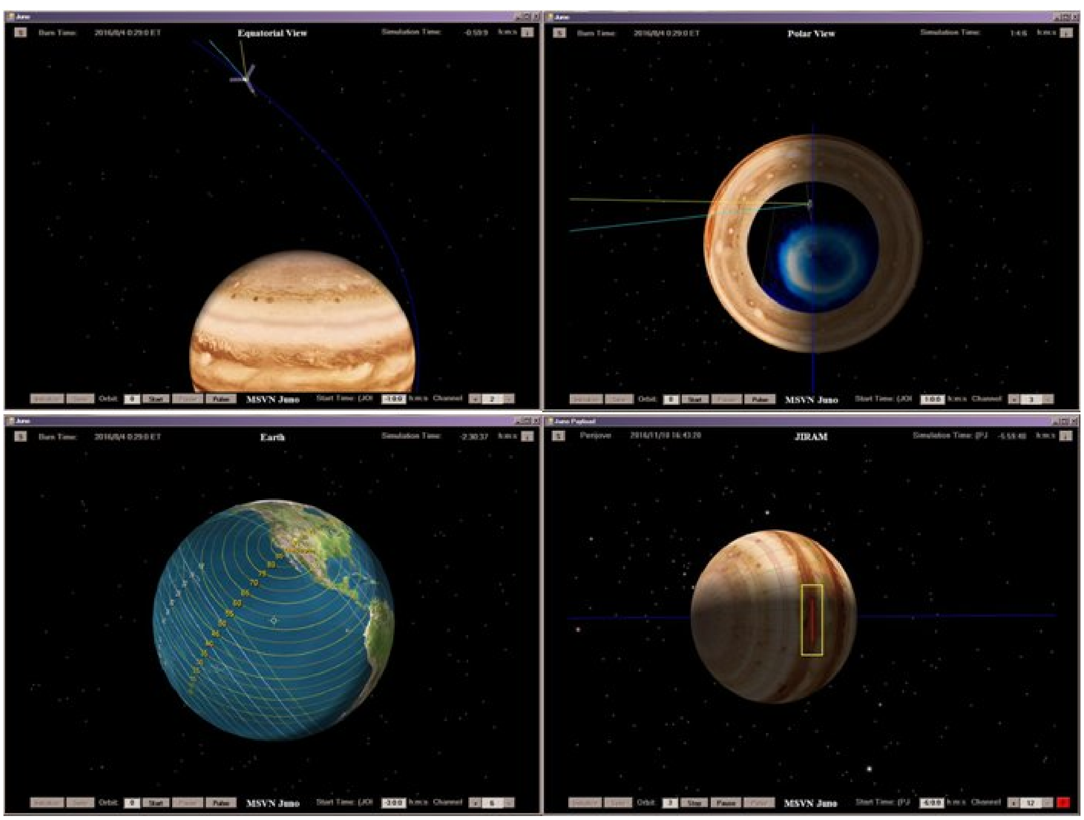

Figure 3. Equatorial (upper left), Polar (upper right), DSN (lower left), and Instrument FOV (lower right) Channels

4. SIMULATION PRODUCTS

The formulation phase of a project is divided into pre-phase A (advanced concept design), phase A (concept design), and Phase B (preliminary design). During the formulation phase, a mission concept is progressively refined, and comprehensive design trades are performed among the spacecraft system, payload system, and mission system. At each stage of requirement derivation, from project-level to system-level and from system-level to subsystem-level, the level-specific design trades are made. A derived requirement is validated against its parent requirements, and a design is verified against the requirement. The Juno mission system team derives its requirements from the project-level requirements including science return, launch timeline, mission duration, and planetary protection. The mission and navigation design and mission operation system implementation are verified against the requirements.

In support of mission and navigation design verification and mission operation system requirement validation, MSVN-Juno has developed a virtual flight system, a virtual ground system, and a virtual world, and performed virtual Juno mission covering several critical mission phases and science observation events. The virtual Juno flight system was developed to represent the operation behavior of the flight system based on the information provided by the flight system team. The virtual Juno ground system was developed to represent the command uplink, data downlink, and data distribution processes. The virtual Juno world was developed to represent the science targets and environmental phenomena information including magnetic field, aurora, and radiation. The level of details for representing the operation behavior is controlled by the availability and relevancy of the information. In this section, the simulation products developed during Phase A and Phase B will be presented with respect to the mission phase, temporal coverage, and design verification.

Phase-A Simulation Products

Juno mission concept proposal was one of the two proposals selected by the NASA's New Frontiers program to proceed to the concept design phase. In order to demonstrate the feasibility of the proposed mission concept, the simulation team developed several simulation systems integrating a preliminary trajectory design, a low resolution spacecraft structure model, and a limited set of activity timelines. Table 1 summarizes the simulation system capabilities with respect to coverage duration and three types of mission models to represent mission design, flight system, and environment. These products were used to introduce the mission objectives to the reviewers, the science investigators, and the public. A brief summary of the four major simulation systems is given below.

Earth Flyby Simulation was used to verify trajectory design of the Earth flyby with respect to solar conjunction, the Earth keep out zone for the microwave radiometer, and instrument calibration opportunities.

Jupiter Flyby Simulation was used to verify the JOI activity timeline and the science orbit attitude for microwave radiometer and gravity science. For the science orbit attitude verification, the orientation of the spacecraft with respect to Jupiter, the Sun, and the Earth during ±3 hours around the perijove was simulated.

Microwave Radiometer (MWR) FOV Simulation was used to examine the cant angle variation during MWR orbit by simulating the footprint layout and its overlap pattern as a function of spacecraft cant angle.

Web Simulation was used to verify the surface coverage during the 30 science orbits, achieving 24-degree separation during the first 15 orbits and 12-degree separation during the second 15 orbits.

Table 1. Simulation Products during Concept Design Phase

Simulation System	Mission Phase	Coverage Duration	Mission Design	Flight System	Environment
Earth Flyby	Earth Flyby	Closest approach +/- 1 hour	trajectory spin rate	solar panel high gain antenna instrument FOV	solar conjunction Earth visibility
Jupiter Flyby	JOI & orbits 1-34	Perijov +/- 3 hours	trajectory spin rate main engine burn attitude control	solar panel high gain antenna instrument FOV	Sun direction Earth direction Jupiter
Web	orbits 2-33	Perijov +/- 1 hour	trajectory		Jupiter
MWR FOV	MWR orbits	Perijov +/- 10 hours	trajectory spin rate attitude control MWR FOV	high gain antenna	Sun direction Earth direction DSN stations Jupiter
Complete orbit	orbits 1-34	11 days per orbit	trajectory attitude control	high gain antenna	Jupiter Earth

Phase B Simulation Products

In September of 2007, the Juno mission was selected to be the next scientific investigation in the NASA New Frontiers Program. Currently, the Juno mission is in preliminary design phase. During the preliminary design phase, the mission system team optimizes trajectory design, develops operation scenarios, and specifies mission operation processes in collaboration with the flight system team and the science investigation team. The main focus of mission simulation is science measurement and data-return verification. The Juno payload system would include: JADE (Jovian Auroral Distributions Experiment), UVS (Ultraviolet Spectrograph), MWR (Microwave Radiometer), Magnetometer, multiple star cameras, and visible and infrared imagers. JADE would study the population of particles making up Jupiter's aurora by measuring electrons and ions along Jupiter's magnetic field lines. UVS would provide images taken directly above the north and south poles of Jupiter, a perfect vantage point to view the entire aurora at once. MWR would measure the amounts of ammonia and water. The magnetometer would measure the magnetic fields in very high resolution, and the imagers would take movies of Jupiter's clouds and satellites.

The science measurement and data-return simulation requires modeling of science phenomena, instruments, on-board resources, and operation control. The science phenomena models include aurora, magnetic field, gravity field, radiation field, and clouds. The instrument models include FOV, obscuration-free zone, data rate, and data volume. The on-board resource models include power, storage, and processor. The operation control models include uplink, downlink, and ground systems. The MSVN-Juno framework was developed to integrate these models, instrument observation simulation, end-to-end data flow simulation, and magnetic field line simulation systems. Table 2 summarizes the preliminary design-phase simulation products, and Figure 4 shows example views.

The end-to-end dataflow system illustrated in Figure 5 models the entire dataflow chain starting from instrument data acquisition to science telemetry distribution to the science investigators. The simulation is divided into an on-board system (light gray panel) and a ground system (dark brown panel). The on-board system simulates the sequence manager, the instruments, the telemetry system, and the downlink process. The ground system simulates sequence planning, merging for uplink processing and telemetry processing, distribution, and analysis for the downlink process. The data rate and volume at each stage represent either design specification or requirements for corresponding subsystems (instrument, command and data handler, telecom, and ground system).

An operation time line for end-to-end data flow simulation employs a set of pseudo subsystem commands dictionary and a command sequence format for specifying subsystem-level operation timelines. The command format is composed of start time, duration, command, and operation parameters. The start time may be specified relative to a predefined time variable or relative to the previous command start time. The subsystem-level operation timeline allows concurrent control and state tracking for instruments, on-board memory, telecom, uplink and downlink processes, and science data distribution.

The end-to-end data flow simulation system provides three simulation control modes, interactive, time-based, and event-based. In the interactive mode, the simulation step is progressed one command at a time based on the user prompt. In the time-based mode, the simulation clock is progressed in regular intervals, and the command sequence is executed as the simulation clock reaches the command time. In the event-based mode, the simulation clock is progressed to the next command time automatically by employing a duration-dependent time interval.

Table 2. Preliminary Design-Phase Simulation Products

Simulation	Payload system	Orbits	Coverage Duration	Analysis
Payload	MWR (microwave radiomater)	3,5,6,7,8	Perijove +/- 1 hours	footprint layout and spin rate footprint overlap and cant angle
	JIRAM (Jupiter infrared auroral mapper)	3,5,6,7,8	Perijove +/- 10 hours	footprint location mirror scan rate and exposure duration visibility of Jovian satellites
	ASC (advanced stellar compass)	1-33	Perijove +/- 1 hours	line of sight and FOV obscuration cant angle impact lit side of Jupiter visibility
End-to-end Dataflow	All instruments	3,4	entire orbit	data acquisition rate data volume downlink anomaly & recovery
Mag Field Line	N/A	1-34	Perijove +/- 3 hours	levels 1-16 SC position and magnetic field line reference aurora

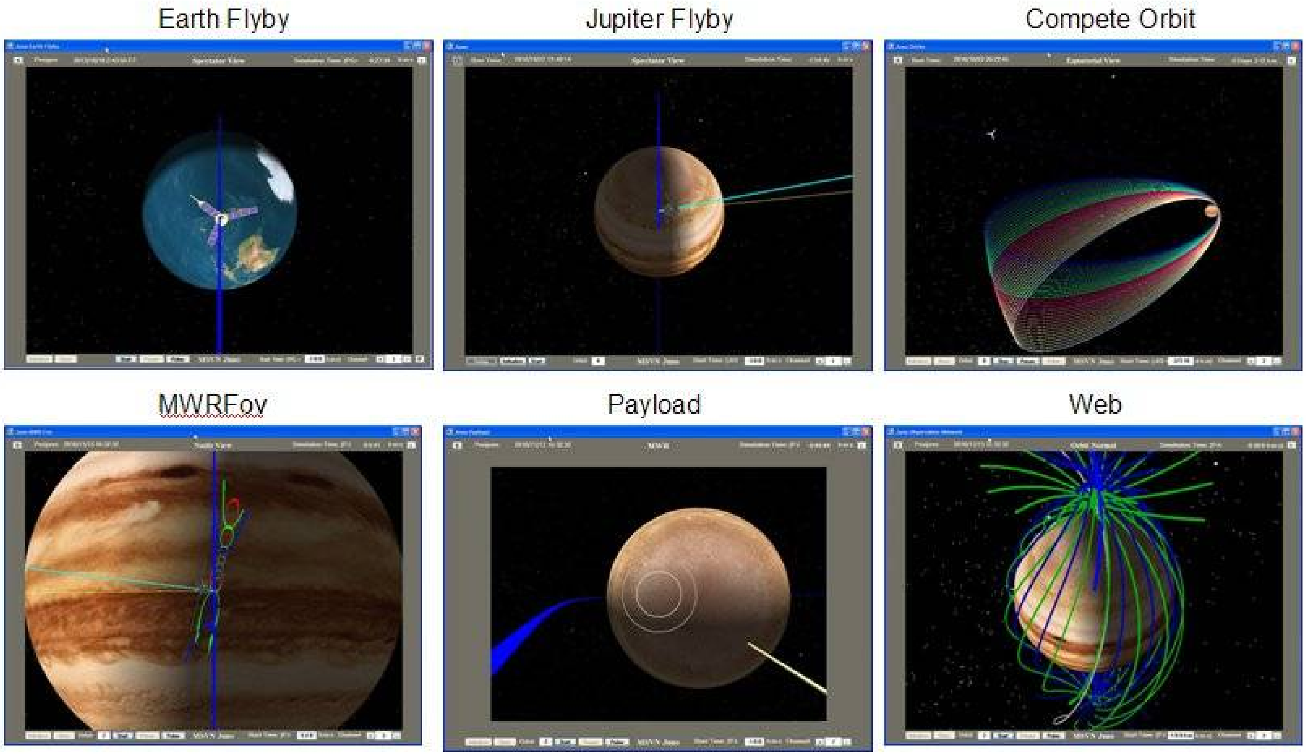

Figure 4. Juno Mission Simulation Products

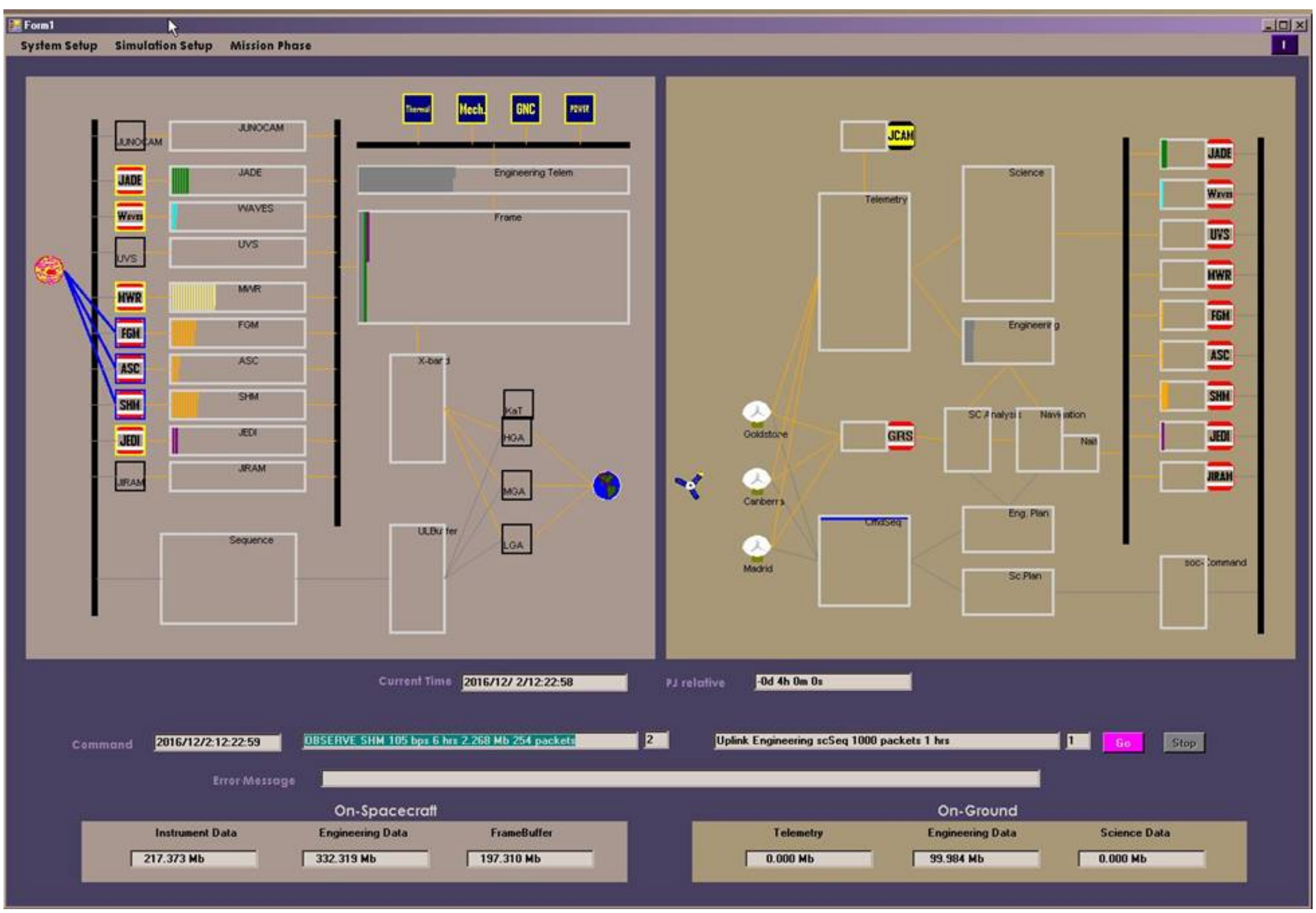

Figure 5. End-to-End Dataflow System

5. CONCLUSION

Figure 6 depicts a collaborative engineering design environment the authors have accomplished for many deep space missions including Mars Odyssey, Cassini, and Juno. As illustrated in this figure, a space science mission starts with a set of science questions about natural phenomena, and it evolves into specific measurement objectives and science-return requirements. The measurement objectives and science-return requirements drive the requirements for the mission operation, spacecraft system architecture, and instrument systems. To ensure the desired quantity and quality of the science data products while minimizing the cost and risk, a lifecycle-wide model-based engineering process that can easily adapt to a mission-specific science traceability matrix must be established. The lifecycle-wide model-based engineering process has been approached by implementing a distributed model service framework that can integrate subsystem discipline models, a virtual simulation framework that can execute operation scenarios, and visualization framework that can represent subsystem-level perspectives. The model-based engineering process enables concurrent and collaborative system engineering among the instrument system, the spacecraft system, and the mission operation [6,7].

In order for a mission to be successful, everyone must work together toward the same mission objectives and clearly understand his/her role in achieving those objectives. The challenges in providing a lifecycle-wide continuity to all mission teams are enormous due to the typical long duration of a mission lifecycle, the multiple engineering teams involved in each lifecycle phase, the multiple engineering disciplines involved in each engineering team, and so on. The transition of engineering teams from one phase to the next introduces many technical and managerial challenges. In particular, disconnects between the design team and the operation team have often been major drivers for high operation cost and mission risk. How can a mission:

a. Share accurate understanding of operational objectives among all mission teams?

b. Validate operability of a system before it is built?

c. Verify science return before receiving telemetry?

These are some of the important questions that the Juno mission simulation team has been addressing and will continue to research throughout the Juno project lifecycle.

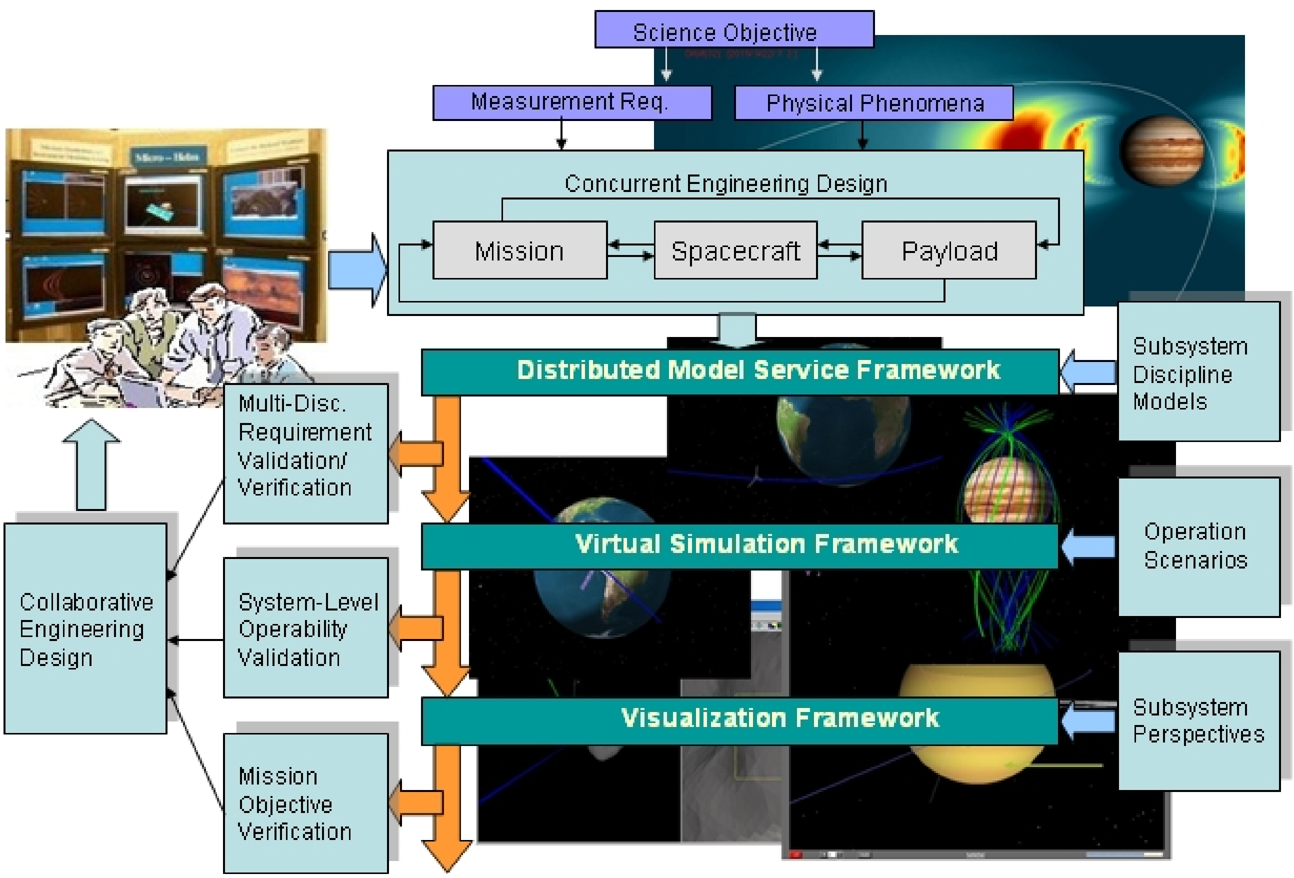

Figure 6. Collaborative Engineering Design Environment

6. References

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Biography

Meemong Lee *is a principal engineer at the Jet Propulsion Laboratory in the areas of modeling and simulation. Her current research activities include model-based collaborative engineering frameworks, sensor-web operation design architecture, and simulation-based measurement requirement formulation. She is also responsible for mission simulation system development for NASA's Juno project. She has a bachelor's degree in electronics engineering from Sogang University in South Korea, a master's degree in computer science from Oklahoma State University, and a doctoral degree in electrical engineering from Oklahoma State University.*

Richard J. Weidner *is a principal technologist at the Jet Propulsion Laboratory in the areas of multi-disciplinary technology development. He led mission simulation and instrument modeling group at JPL during 1998–2006. He has invented numerous real-time distributed mission simulation systems including SIMP-SASED for Mars Pathfinder's panorama imaging camera, Micro-Helm for Mars Odyssey, and MSVN-Cassini for Cassini-Saturn Orbit Insertion. He is currently developing multi-dimensional phenomena models for Juno mission simulation and Earth atmospheric mission simulation .He has a bachelor's degree, a master's degree, and doctoral degree in Electrical Engineering from Oklahoma State University.*